



Silverstone, J. W., Wang, J., Bonneau, D., Sibson, P., Santagati, R., Erven, C., O'Brien, J. L., & Thompson, M. G. (2016). Silicon Quantum Photonics. In *2016 International Conference on Optical MEMS and Nanophotonics (OMN 2016): Proceedings of a meeting held 31 July - 4 August 2016, Singapore* [Tu2.10-1] Institute of Electrical and Electronics Engineers (IEEE).
<https://doi.org/10.1109/OMN.2016.7565856>

Peer reviewed version

Link to published version (if available):
[10.1109/OMN.2016.7565856](https://doi.org/10.1109/OMN.2016.7565856)

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Silicon Quantum Photonics

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Abstract— Silicon integrated quantum photonics has recently emerged as a promising approach to realising complex and compact quantum circuits, where entangled states of light are generated and manipulated on-chip to realise applications in sensing, communication and computation. Recent highlights include chip-to-chip quantum communications, programmable quantum circuits, chip-based quantum simulations and routes to scalable quantum information processing.

I. INTRODUCTION

Photonics is a promising approach to realising quantum information technologies, where entangled states of light are generated and manipulated to realise fundamentally new modes of computation, simulation and communication [1], as well as enhanced measurements and sensing. Historically bulk optical elements on large optical tables have been the means by which to realise proof-of-principle demonstrators in quantum physics. More recently, integrated quantum photonics has enabled a step change in this technology by controlling and manipulating single photons within miniature waveguide circuits [2]. This technology approach is now being used to pioneered breakthroughs in quantum communications, quantum sensing and quantum information processing. Here we present recent developments in chip-to-chip quantum communications and on-chip quantum information processing.

II. CHIP-SCALE QUANTUM KEY DISTRIBUTION

Quantum Key Distribution (QKD) is one of the first commercially available quantum technologies and provides a means for distributing shared secret random keys between two users (Alice and Bob) in order to encrypt information sent between them. Here, we present the first demonstration of a fully integrated chip-to-chip QKD system, allowing quantum communications and cryptography to enjoy the benefits of miniaturisation, reliability and reconfigurability that integrated photonics provides. The phase stability of integrated photonics makes it particularly suitable for manipulating quantum information encoded in different time-bins, an encoding extensively used in fibre-based QKD communication systems.

Communication requires the fast encoding of information, and QKD has stringent requirements on the level of fidelity for the preparation and measurement of states. Commonly, this requires ideal phase or polarisation modulation, often achieved with lithium-niobate electro-optic modulators, but to allow large-scale integration of many components, more compact technologies like silicon-on-insulator are to be adopted. Unfortunately, silicon lacks a natural $\chi(2)$ non-linearity, and

therefore fast modulation is commonly achieved using carrier-depletion or injection methods, where doping of the waveguide can form p-n or p-i-n diode structures than can be reversed biased to deplete the waveguide of carriers, or forward biased to inject carriers in to the waveguide, interacting with the optical mode. These methods can be operated and multi-GHz rates [6], but also incur a number of non-idealities, including high levels of insertion loss, phase-dependent loss, and saturation (the maximum phase induced in carrier depletion modulation will be limited dependent on the length and the doping present), which presents a challenge for QKD state preparation.

To overcome these issues, ideal but slow thermo-optic phase modulators are included to allow a DC bias at the $|+i\rangle$ state, and four carrier-depletion modulators are designed to only require π phase shift towards each of the BB84 states. This therefore reduces the phase dependent loss incurred, and ensures that the modulator can reach the required phase given a $\leq 1.5\text{mm}$ length, allowing for fast modulation. We demonstrate this principle with two designs; one for polarisation encoding, and one for time-bin encoding

The polarisation encoded system uses a Mach-Zehnder interferometer (MZI) to prepare a path-encoded state, with the phase modulators set to a DC value of $|+i\rangle$, and the modulators on the inside of the MZI encoding $|0\rangle$ and $|1\rangle$ states, and the modulators outside the interferometer encoding $|+\rangle$ and $|-\rangle$. The path encoded state is then combined on a two-dimensional grating coupler to convert from path to polarisation (P2P) [7]. With a passive fibre receiver based on polarisation-beamsplitters, and superconducting nanowire single photon detectors, we demonstrate low error rate ($\sim 20\text{dB}$ extinction) polarisation encoded BB84.

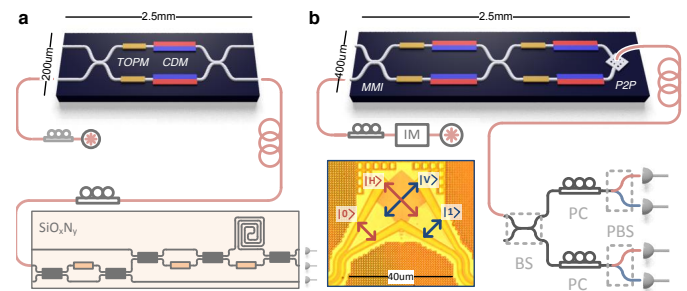


Figure 1: Chip-to-chip QKD devices

The time-bin encoded system uses a unbalanced asymmetric MZI to temporally separate a weak coherent pulse in to two time intervals, using a on-chip delay of 1.5ns and an MZI to balance the loss on the short arm, allows for the DC preparation of $|+i\rangle$ with the last MZI set to 50:50 splitting ratio.

The carrier depletion modulators on the inside of the AMZI are used to prepare the X basis states, and the modulator on the final MZI allow the routing of either the first or second time bin to the output arm, therefore preparing the Z basis states. With a passive integrated AMZI receiver, and superconducting nanowire single photon detectors, we again demonstrate low error rates ($\sim 20\text{dB}$ extinction) time bin encoded BB84.

This work experimentally demonstrates the feasibility of QKD transmitters, for high-speed QKD, based on CMOS-compatible silicon photonics integrated circuits. The ability to scale up these integrated circuits and incorporate microelectronics opens the way to new and advanced integrated quantum communication technologies and larger adoption of quantum-secured communications.

III. CHIP-SCALE QUANTUM INFORMATION PROCESSING

The silicon-based quantum technology platform, where quantum states of light can be generated and manipulated using entirely silicon-based waveguide circuits [3], offers a range of benefits for quantum photonics, including high nonlinearities for efficient on-chip generation of quantum states of light, and high component densities for complex circuits. Figure 2 presents a silicon-based quantum circuit able to generate and analyse two maximally entangled qubits.

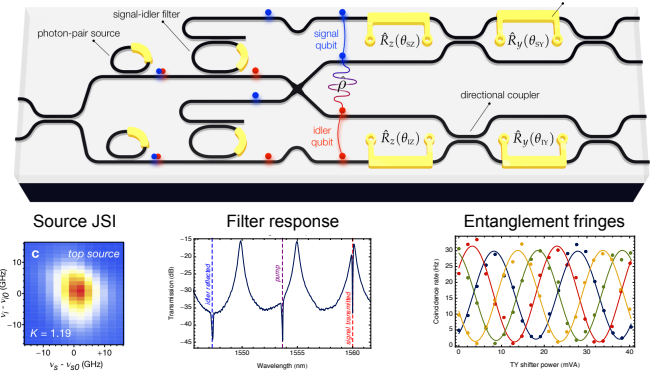


Figure 2: Integrated quantum circuit for on-chip Bell state generation and analysis

Using this device we observe high-visibility interference between photon pairs from different microring sources, and generation of the entangled Bell state. Path-encoded qubits are realised through the phase-stable frequency-selection elements, and on-chip quantum state tomography is performed using the integrated Mach-Zehnder interferometers, confirming the entanglement of the generated Bell state with a fidelity of 0.88. Other key component for quantum photonics circuits include on-chip filters, high precision Mach-Zehnder interferometers, and on-chip detectors. This technology approach paves the way towards a fully integrated platform for quantum technologies, where the photon sources, circuits and detectors can all be integrated onto the same chip, and in a technology platform where very high component densities are feasible – providing a route to high-performance and large-scale quantum information technologies.

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